Airflow through Mine Openings and Ducts

Chapter 5

Fundamentals of Airflow

- Ventilation— the application of the principles of fluid mechanics & thermodynamics to the flow of air in underground openings
- *Fluid mechanics* – deals with the action of forces;
- *Thermodynamics* – concerned with the heat and work on the properties/substances

Fundamentals of Airflow

- A fluid: always a continuous medium & there can be no voids in it.
- Properties of a fluid (density, temperature, composition) may vary from place to place.
- Frictionless (ideal) fluid: if the neighboring layers offer no resistance to the movement of fluid – non-existent in nature.

Fundamentals of Airflow

- Compressive forces: tend to change fluid volume, and in turn its density. Compressive flow vs. incompressive flow.
- In a flowing fluid, each particle changes position with a certain velocity. The magnitudes and directions of the velocities of all particles may vary with position and time.

Turbulent vs. Laminar flow

- Streakline – an imaginary line in a fluid, the tangent to which gives the direction of the velocity at that position
Turbulent vs. Laminar Flow

- **Laminar flow (streamlined flow)** – if the streamlines are smoothly curved and almost parallel to each other

- **Turbulent Flow** – if the streamlines are arranged haphazardly

Energy Changes in Fluid Flow

- **Friction & shock Energy losses**
- **Heat energy added or removed**
- **Work energy added or removed**

Total energy\(_1\) = total energy\(_2\) + flow energy losses\(_{1,2}\)

- **Mine ventilation** – Steady flow process with transitions and losses in energy involved.

\[ F = P_1 yz - P_2 yz + B \omega \omega \omega \omega \]

- **Work** = body or mass force per unit mass \(\omega\)

- **Heat** = constant fluid density \(\omega\)

- **Energy losses**

\[ F = (V_2 - V_1)/t \]

If taken vertically –

\[ V_2 \uparrow \quad P_2 \]

\[ H_2 \]

\[ V_1 \uparrow \quad P_1 \]

\[ H_1 \]
If taken vertically –

\[ P_1 \text{ & } V_1 \text{ are at height } Z_1; \ P_2 \text{ & } V_2 \text{ are at height } Z_2; \text{ Distance } x = Z_2 - Z_1 \]

\[ B \Rightarrow \text{due to gravitation, and } B = -g \]

\[ P_1 - P_2 - g \omega (Z_2 - Z_1) = \omega (V_2^2 - V_1^2)/2 \]

Bernoulli’s Equation for the ideal incompressible fluid in terms of pressure (conservation of momentum)

\[ P_1 + \omega V_1^2/2 + g \omega Z_1 = P_2 + \omega V_2^2/2 + g \omega Z_2 \]

Divide both sides by \( wg \),

\[ P_1/\omega + V_1^2/2g + Z_1 = P_2/\omega + V_2^2/2g + Z_2 \]

Bernoulli’s Equation (SI units) for ideal incompressible fluid in pressure head;

\[ P_1/\omega + V_1^2/2g + Z_1 = P_2/\omega + V_2^2/2g + Z_2 \]

Bernoulli’s Equation in pressure head (British units); Eq. 5.3, p. 136 in text

\[ p = \text{pressure} \]

\[ w = \text{specific weight} \]

\[ V = \text{velocity} \]

\[ \mu/w = \text{static energy} \]

\[ V^2/2g = \text{velocity energy} \]

\[ Z = \text{potential energy} \]

\[ H_f = \text{flow energy loss} \]

Energy Changes in Fluid Flow

Bernoulli Equation

Incompressible Fluid

\[ p_1/\omega + V_1^2/2 + g \omega Z_1 = p_2/\omega + V_2^2/2 + g \omega Z_2 \]

\[ p_1/\omega + V_1^2/2g + Z_1 = p_2/\omega + V_2^2/2g + Z_2 \]

\[ H_t_1 = H_t_2 + H_f \]

where \( H_t \) is total head
Energy Changes in Fluid Flow

It can also be expressed as:

\[ H_{S1} + H_{V1} + H_{Z1} = H_{S2} + H_{V2} + H_{Z2} + H_l \]

where

- \( H_S \) – static head
- \( H_V \) – velocity head
- \( H_Z \) – elevation or potential head
- \( H_S \) – static head

Modified Energy Equation

By eliminating the elevation terms and using gage pressures for static and velocity heads, the following equation can be used:

\[ H_{S1} + H_{V1} = H_{S2} + H_{V2} + H_l \]

Using absolute pressures works as well, but the customary practice is to use gage pressures.

Can’t do this for natural ventilation.

Head Losses

&

Mine Heads

(Head and Pressure will be used interchangeably from here on)

Head Losses in Fluid Flow

- Energy supplied by natural or mechanical means is necessary to overcome flow losses underground
- This energy supply consists of static head & velocity head, but only static head is available for moving the airflow

\[ H_{\text{gain}} = H_s + H_v \]

- With changes in velocity, some conversion to static head may occur, even though some shock loss occurs

Overall or Mine Heads

- Engineers will often, in planning, want to sum all of the expected flow-energy losses to determine the amount of head that must be supplied to overcome them and produce the desired airflow.

\[ H_{\text{gain}} = \Sigma H_L = \Sigma (H_f + H_x) \]

- In a mine ventilation system with a single fan and a single discharge, the cumulative energy consumption is called the total mine head.
Overall or Mine Heads

- The mine head is really a difference in head to move the desired quantity of air.
- We’ll look at a few definitions next to understand the nature of airflow, but they cannot be applied to multiple fan or multiple discharge systems.

Mine Static Head

- It is the energy consumed to overcome all flow head losses
- Mine $H_s = \Sigma H_L = \Sigma (H_f + H_x)$
- Applies to a series or series-equivalent system
- Includes all decreases in total head between entrance and discharge

Mine Velocity Head

- It is the velocity head at the discharge of the system
- It is not a cumulative head loss
- It changes throughout the system as the airways change
- It is a loss because the kinetic energy of the air is lost upon discharge

Mine Total Head

- It is the sum of all energy losses in the system:
- Mine $H_t = \text{mine } H_s + \text{mine } H_v$

Head Gradients for Simple Mines or Airways or Ducts

Blowing System

*FIGURE 3.5* Head gradients for a blower system in mine ventilation.
Blowing System – Example 5.2

Exhaust System

Booster System

State of Airflow in Mine Openings

For air at normal temperatures:

\[ N_{Re} = 6250DV \]

where \( D \) – diameter of airway, ft
\( V \) – velocity of air, fpm

State of Airflow in Mine Openings

Critical velocity is the velocity for a given airway corresponding to an \( N_{Re} \) of 4000 (boundary for turbulent flow):

\[ V_c = \frac{38.4}{D} \]

- It is important to maintain turbulent flow in mine airways
- Velocities over 13 fpm will nearly always give turbulent flow
- Exceptions: gob flow, leakage

State of Airflow in Mine Openings

- Laminar, intermediate, and turbulent flow
- Reynolds number used to establish boundaries between them
- Laminar flow up to \( N_{Re} \) of \( \approx 2000 \)
- Turbulent flow above \( N_{Re} \) of \( \approx 4000 \)
Effect of State of Flow on Velocity Distribution

![Graph showing velocity distribution](image)

* $N_r \text{ usually } > 10,000$
* Estimate $V_{ave} = 0.8 V_{max}$

Effect of State of Flow on Velocity Distribution

![Graph showing velocity distribution in circular conduits](image)

Calculations of Head Losses

Velocity Head

$$H_v = w \left(\frac{V}{1,098}\right)^2$$

- $V$ – fpm
- $H_v$ – in. water

For standard air at sea level $w = 0.075$ lb/ft$^3$, thus:

$$H_v = \left(\frac{V}{4,009}\right)^2$$

Friction Loss

- Accounts for 70-90% of head loss in a mine
- It is a loss of static pressure because of drag or resistance to airflow; also internal friction of fluid itself
- It is a function of velocity of flow, surface characteristics of airway, and the dimensions of the airway

Friction Loss

We'll start with the well-known Darcy-Weisbach equation from fluid mechanics for friction loss in a circular duct:

$$H_l = f \frac{L V^2}{D 2g}$$

You know the units well by now.
Note: $f$ is the coefficient of friction.
Friction Loss
By using the hydraulic radius, given below, the equation can be converted for general-shaped ducts:

\[
R_h = \frac{A}{O}
\]

After substituting, the Atkinson equation for friction loss in mine ventilation can be derived (next slide).

Atkinson Equation – Most Used Form

\[
H_f = \frac{KOLQ^2}{5.2A^3}
\]

- \(H_f\) – friction head loss, in. water
- \(Q\) – air quantity, ft³/min
- \(K\) – empirical friction factor, lb.min²/ft⁴
- \(O, L\) – perimeter & length, ft
- \(A\) – area, ft²

Notes on Friction Factor, \(K\)
- It is not a constant, but varies directly with air specific weight
- Values of \(K\) are commonly expressed in tables at standard air specific weight
- It corresponds to the coefficient of friction in general fluid flow

Notes on Friction Factor, \(K\)
- Relationship between \(K\) and \(f\):
  - \(K \approx 800 \times 10^{-10} f\)
  - \(K\) is assumed constant for a given airway, regardless of \(N_{Re}\)
  - \(H_f\) actually varies with velocity to a power between 1.75 and 2
  - Any departure is generally disregarded
  - For laminar flow, the exponent is near 1

Determination of \(K\)
- Only accurate way to determine the friction factor for an airway is to compute it from the pressure drop measured in the mine
- For estimation or projection purposes, they may have to be selected from experience
- Table 5.1 gives BoM values from exhaustive tests in metal mines
- Also Table 5.2 (Kharkar et al.)
Determination of $K$

- Kharkar’s values ~ 5-20% lower for similar conditions
- McPherson values for longwall faces: $200 \text{ to } 350 \times 10^{-10} \text{ lb.min}^2/\text{ft}^4$
- McPherson values for shafts with different wall constructions, structural obstructions, and conveyances

There are some precautions to follow when using values from tables

Precautions for Using Tabled $K$ Values

- Multiple values from tables by $10^{-10}$ and use proper units
- Use experimental values determined in a mine, preferably for airways of known length and constant cross section
- Correct $K$ for actual $w$ using:
  \[ \text{Corrected } K = K_{\text{table}} (\omega / 0.0750) \]
- Select $K$ carefully for conditions prevalent in an airway

Precautions for Using Tabled $K$ Values

- When in doubt, use average $K$ values
- Italicized values commonly occur and are safe to use
- For noncoal mines, use Table 5.1 values
- For coal mines, use Table 5.2 values
- If the airway is timbered and the sets are spaced on other than 5-ft centers, modify $K$ according to Fig. 5.11
- If roof bolting used, assume an unlined airway

Adjustments for Timber Sets

\[
\begin{array}{c|c|c|c}
\text{Pipe or Tubing} & \text{Friction Factor} \\
\hline
\text{Steel, wood, fiberglass (rigid)} & 15 (0.0028) \\
\text{Jute, canvas, plastic (flexible)} & 20 (0.0037) \\
\text{Spiral-type canvas} & 22.5 (0.0042) \\
\hline
\text{Good, New} & \text{Average, Used} \\
\end{array}
\]

Friction Factor for Vent Pipe

- Simplified way to approximate $K$
- Fig. A.2 in the appendix
- Friction loss per 100 ft of airway
- For ventilation pipe or tubing, use Fig. A.3; values are for circular sheetmetal ducts in good condition; correction factor on p. 158 of your book for other conditions
- Values from graph actually more accurate than calculated values; examples pp. 159

Estimation of Friction Loss by Graph

- FIGURE 5.11 Effect of spacing of timber sets on friction factor $K$. (After McElroy, 1953)
Shock
Loss

Calculation of Shock Loss

- Direct calculation for velocity head
- Calculation by increase in friction factor
- Calculation by equivalent length method

Direct Calculation of Shock Loss

\[ H_s = X H_v \]

- Every bend, area change, and obstruction has its own shock-loss factor, \( X \) (dimensonless)
- Direct calculation rarely used; too inaccurate (small values)
- Look in references, if needed

Shock Loss by Increasing Friction Factor

- Simple but inexact procedure
- Can yield acceptable results if done well
- Especially useful in large system with many shock losses

Shock Loss by Equivalent Length Method

- Recommended method
- Values have been calculated by equating the formulas for friction loss and shock loss, then solving for \( L_e \), equivalent length of airway

<table>
<thead>
<tr>
<th>Source</th>
<th>( R )</th>
<th>( L_e )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bend, acute, round</td>
<td>3</td>
<td>(5)</td>
</tr>
<tr>
<td>Bend, acute, sharp</td>
<td>150</td>
<td>(45)</td>
</tr>
<tr>
<td>Bend, right, round</td>
<td>1</td>
<td>(3)</td>
</tr>
<tr>
<td>Bend, right, sharp</td>
<td>70</td>
<td>(20)</td>
</tr>
<tr>
<td>Bend, oblique, round</td>
<td>1</td>
<td>(3)</td>
</tr>
<tr>
<td>Bend, oblique, sharp</td>
<td>15</td>
<td>(5)</td>
</tr>
<tr>
<td>Doorway</td>
<td>70</td>
<td>(20)</td>
</tr>
<tr>
<td>Overflow</td>
<td>65</td>
<td>(20)</td>
</tr>
<tr>
<td>Initial</td>
<td>20</td>
<td>(8)</td>
</tr>
<tr>
<td>Discharge</td>
<td>65</td>
<td>(20)</td>
</tr>
<tr>
<td>(20% of airway area)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(40% of airway area)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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Precautions When Calculating Shock Loss by Equivalent Length Method

- Values from Table 5.3 need not be corrected for most problems.
- With a change in area (splitting not involved) or an inlet, include the shock loss in the airway section following the change; also for a bend with an area change; discharge is an exception: include in preceding section.

Precautions When Calculating Shock Loss by Equivalent Length Method

- At splits and junctions in airways, use only the portion of the total flow involved in a change of direction or area; values from Table 5.3 assume an even division of flow and allow for bend and area change; include loss at split or junction within the pressure drop for the particular branch.

Combined Head Losses and Mine Heads

- Using the equivalent length method for shock loss permits a single calculation of the overall head loss for a given airway:

\[ H_f + H_x = \frac{KO(L + L_e)Q^2}{5.2A^3} \]

- Mine heads are then found by cumulating the airway head losses.
- This procedure is recommended.

Combined Head Losses and Mine Heads

- Study example 5.7 on pages 163-164 of text.
- It’s a good one.

Air Power

Air power is the power needed to overcome the energy losses in an airstream:

\[ P_a = \frac{5.2HQ}{33,000} \text{ hp} \]

- \( H \) in in. water
- \( Q \) in cfm
- You can find total air power or static air power.